A LAr scintillation veto for GERDA Phase II

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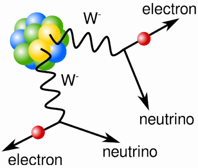
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

GERDA

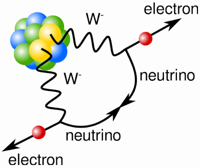
Double beta decays

$2\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\nu_e$



- so far observed in 12 nuclei with half lifes in the range of 10^{18} - 10^{24} *yr*
- $T_{1/2}^{2\nu}(^{76}Ge) = (1.926 \pm 0.095)10^{21}$ yr measured by the GERDA collaboration
  arxiv:1501.02345v1
- $\Delta L = 0$: lepton number conserved
- allowed by the standard model

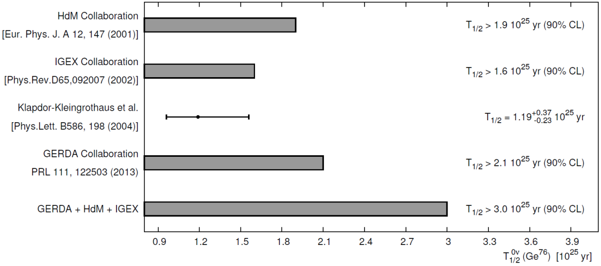
$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$

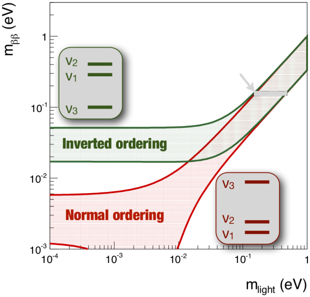


- only if ν has Majorana mass component
- still hunted process
- $\Delta L = 2$: lepton number violation

→ physics beyond the standard model

State of the art of $0\nu\beta\beta$ decay search with ^{76}Ge



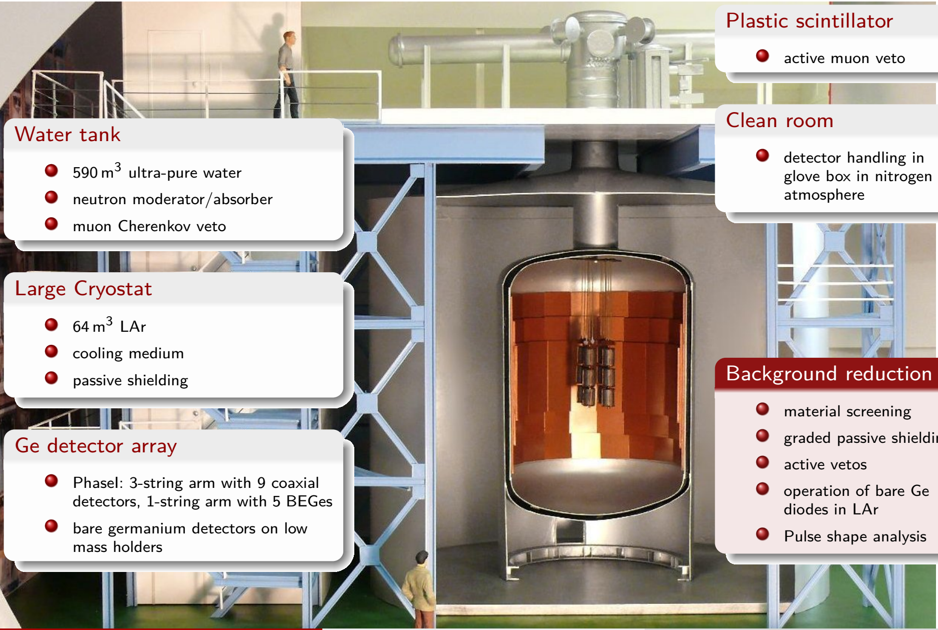


Decay rate (if light Majorana ν exchange is dominating process)

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \langle m_{\beta\beta}\rangle^2$$

- $G^{0\nu}(Q_{\beta\beta}, Z) \propto Q^5_{\beta\beta}$ = phase space integral
- $\left|M^{0\nu}\right|$ nuclear matrix element
- $\langle m_{\beta\beta}\rangle = \left|\sum_{i=1}^{3} U_{ei} m_i\right|$ = effective ν mass

The GERDA experiment



Plastic scintillator

- active muon veto

Clean room

- detector handling in glove box in nitrogen atmosphere

Water tank

- 590 m^3 ultra-pure water
- neutron moderator/absorber
- muon Cherenkov veto

Large Cryostat

- 64 m^3 LAr
- cooling medium
- passive shielding

Ge detector array

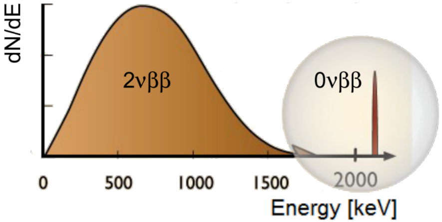
- PhaseI: 3-string arm with 9 coaxial detectors, 1-string arm with 5 BEGes
- bare germanium detectors on low mass holders

Background reduction

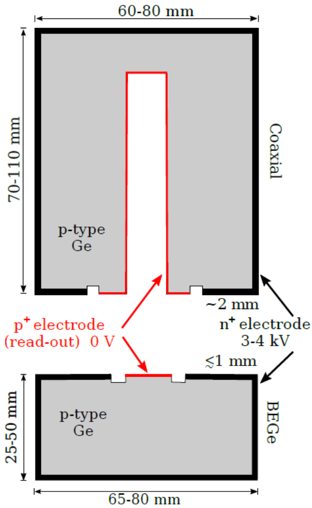
- material screening
- graded passive shielding
- active vetos
- operation of bare Ge diodes in LAr
- Pulse shape analysis

Experimental aspects of $0\nu\beta\beta$ search in ^{76}Ge

Sum electron energy spectrum



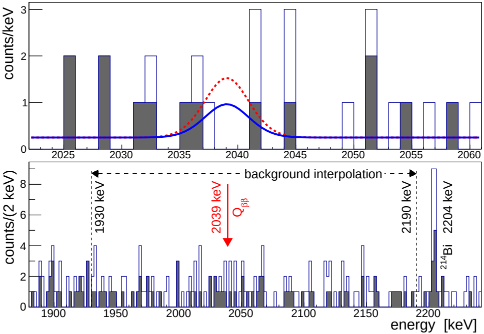
- **source = detector**
  $\rightarrow$ high detection efficiency
- detectors from Ge material enriched to $\approx 87\%$ in ^{76}Ge (coaxial and BEGe)
- stable performance
- $\Delta E \approx 0.1\%$ at $Q_{\beta\beta}$



$\Rightarrow$ main challenge: avoid background at $Q_{\beta\beta}$

$\text{BI} = 1.0(1) \cdot 10^{-2} \frac{\text{cts}}{\text{keV}\cdot\text{kg}\cdot\text{yr}}$

- ➢ design goal fulfilled
- ➢ 10 times better BI than previous experiments



GERDA: 90% lower limit ($T^{0\nu}_{1/2}$) [Phys. Rev Lett. 111 (2013) 122503]

Claim: $T^{0\nu}_{1/2} = 1.19 \cdot 10^{25} yr$ [Phys. Lett. B 586 198 (2004)]

Number of events in $Q_{\beta\beta} \pm 2\sigma_E$ after cuts (gray):

- 2.5 expected background events
- 3 observed
- 6 expected from claim

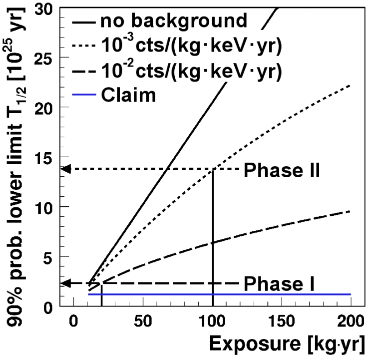
⇒ No signal observed at $Q_{\beta\beta}$

⇒ claim rejected with 99% probability

result on $T^{0\nu}_{1/2}$

frequentist profile likelihood fit

- best fit $N^{0\nu} = 0$
- $T^{0\nu}_{1/2}(90\% C.L.) > 2.1 \cdot 10^{25} yr$
- median sensitivity: $2.4 \cdot 10^{25} yr$



- background, i.e. statistical fluctuation limited scenario

$$T_{1/2}^{0\nu} \propto \sqrt{\frac{M \cdot t}{\Delta E \cdot BI}}$$

- zero background regime

$$T_{1/2}^{0\nu} \propto M \cdot t$$

$M \cdot t$: exposure $[\mathrm{kg} \cdot \mathrm{y}]$, ΔE: energy resolution

BI: background index $[\mathrm{cts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})]$

PhaseII goal: explore $T_{1/2}^{0\nu}$ up to $1.5 \cdot 10^{26}\,\mathrm{yr}$

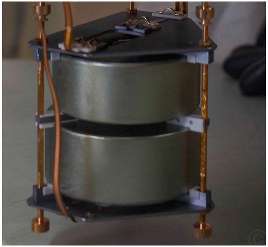
- increase of exposure → increase detector mass
- improved energy resolution
- significant **reduction of background** to re-enter background free regime → BI of 10^{-3} $[\mathrm{cts}/(\mathrm{keV} \cdot \mathrm{kg} \cdot \mathrm{yr})]$

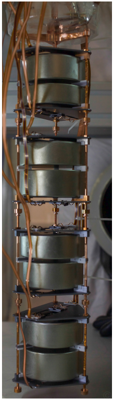
Towards an upgrade of GERDA

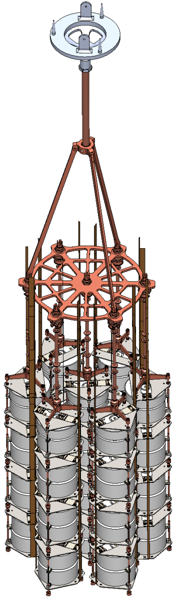
additional 25 new BEGe detectors
$\approx 20\,\mathrm{kg}$ mass (87% enrichment)

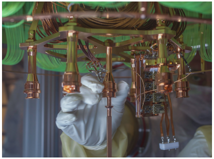
- better energy resolution
- enhanced pulse shape discrimination

new low mass holders with reduced mass and copper partly replaced by silicon





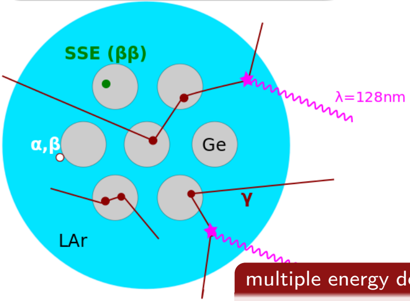




low radioactivity electronics matching the low capacitance of BEGes

$\beta\beta$ event

local energy deposition (SSE)



α or β decays

e.g. ^{42}K, ^{210}Po, on detector surface
→ energy deposition on n^+ or p^+ contact

multiple energy deposition...

... in and outside crystal (MSE)

- external background e.g. ^{214}Bi, ^{208}Tl
- cosmogenic isotopes e.g. ^{60}Co

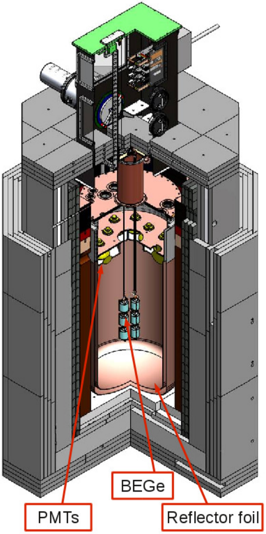
LAr scintillation light

... can be used as anticoincidence veto

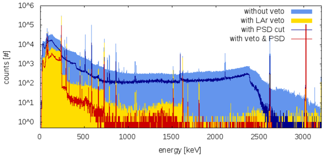
- excited states are created in
  - singlets $\tau \approx 6\,\mathrm{ns}$
  - triplets $\tau \approx 1.5\,\mu\mathrm{s}$
- decay under emission of photons, $\lambda = 128\,\mathrm{nm}$
- in ultra-pure LAr 40000 ph/MeV
- contaminations lead to reduction of triplet lifetime and attenuation length

LArGe - a test facility for GERDA

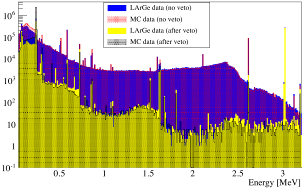
Proof of LAr-veto concept in low background environment



internal ^{228}Th source:



M. Heisel, Taup 2011



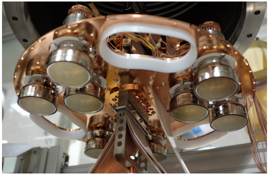
- bg suppression studied for different sources in different locations
- simulation framework extended with photon tracking

⇒ good MC description after tuning and physics validation

source	pos	suppression factor LAr veto	PSD	total	MC (LAr)
^{228}Th	int	1180 ± 250	2.4 ± 0.1	5200 ± 1300	909 ± 235
	ext	25 ± 1.2	2.8 ± 0.1	129 ± 15	17.2 ± 1.6
^{226}Ra	int	4.6 ± 0.2	4.1 ± 0.2	45 ± 5	3.8 ± 0.1
	ext	3.2 ± 0.2	4.4 ± 0.4	18 ± 3	3.2 ± 0.4
^{60}Co	int	27 ± 1.7	76 ± 8.7	3900 ± 1300	16.1 ± 1.3

The hybrid design

3“ photomultiplier tubes (MPIK)



Cu cylinder with wavelength shifting reflector foil

scintillating fibers coupled to SiPMs (developed @ TUM)

Outcome of an extensive MC simulation campaign

goal: optimize the veto design with respect to suppression factors and self-induced background

$$\text{SF} = \frac{\text{total events in ROI}}{\text{unvetoed events in ROI}}$$

- suppression factor PMTs vs. fibers
- vertical position of PMTs and detector array
- loose/dense packing of the array

study the impact of LAr purity (attenuation length)

⇒ LAr veto still gives good SF but pe yield drops

predicted suppression factors for different backgrounds

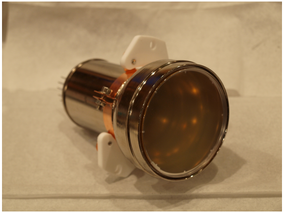
	det. holders	det. surface	hom. in LAr	far away
^{214}Bi	10.3 ± 0.3	3.5 ± 0.1	54.8 ± 7.9	-
^{208}Tl	320 ± 34	-	-	112.1 ± 38.8
^{42}K	-	1*	5.3 ± 0.6	-

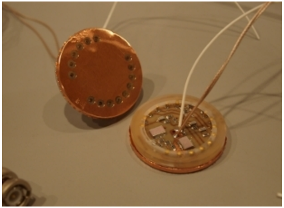
* suppression factors calculated for older designs (approximate values)

self-induced BI

- induced BI $\approx 2.3 \cdot 10^{-5}$ $\mathrm{cts/(kg \cdot keV \cdot yr)}$
- takes into account radioactivity of PMTs, VD, fibers, SiPMs, copper shrouds, reflector foil, cables,...

PMT light readout





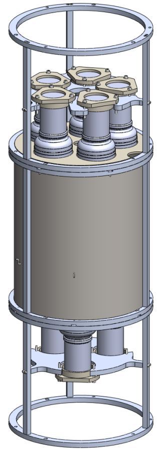
screening results [mBq/pc]

	^{228}Th	^{226}Ra
PMT *	< 1.94	< 1.7
VD	< 0.5	< 1.14

* calculated from component screening

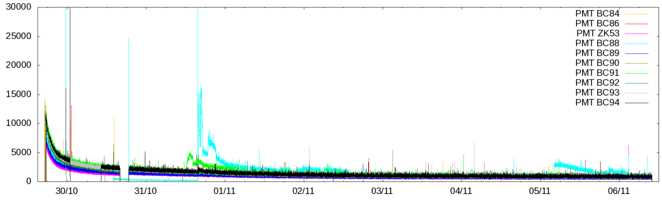
test facility @ MPIK

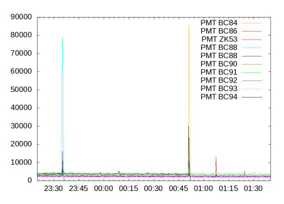
- test of up to 10 PMTs in LAr

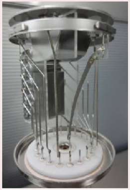


- ➢ low radioactivity PMTs
- ➢ gain calibration with LED
  peak-to-valley ≥ 4
- ➢ afterpulse probability $< 10\%$
- ➢ signal rate monitoring
  low dark-rate: $< 100\,\mathrm{Hz}$ in LN
- ➢ longterm test up to 6 weeks performed
- ⇒ some PMTs exhibited light production

Photomultiplier longterm stability







in LAr: some PMTs exhibited light production

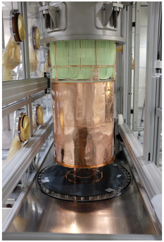
likely cause: discharges of e^- surface charges on ceramic stem

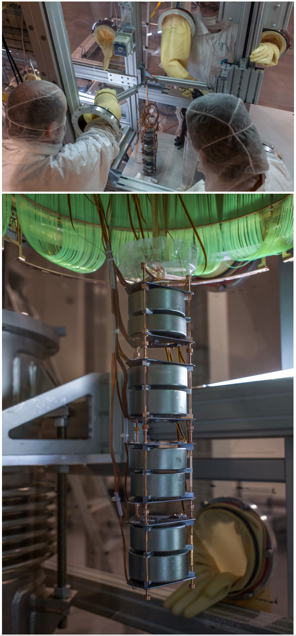
iterative process to study several countermeasures in close cooperation with Hamamatsu:

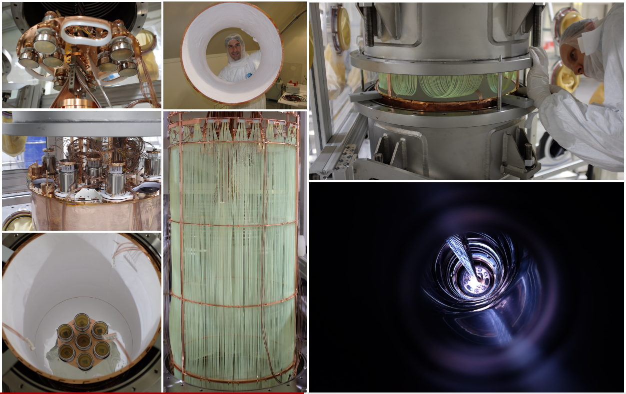
$\Rightarrow$ significant improvement of PMT stability in later versions

- more than 40 PMTs tested for $\geq 40\,\mathrm{d}$ in LAr
- 20% failure rate for latest generation

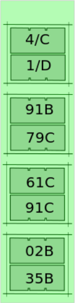
$\Rightarrow$ 16 good ones selected for the operation in GERDA commissioning started in fall 2014



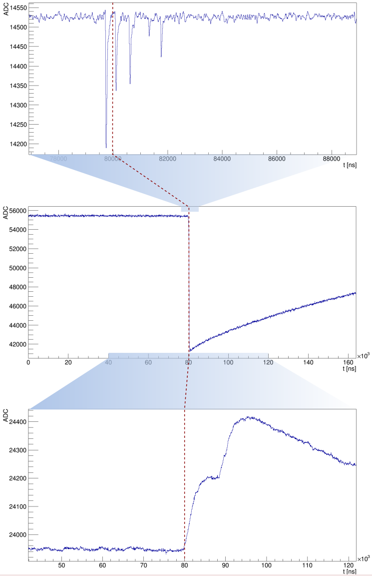




First commissioning data with calibration source



- ➢ five working Ge detectors
- ➢ two calibration sources deployed: ^{228}Th, ^{226}Ra



PMT (x16)

Ge diode (x8)

SiPM (x15)

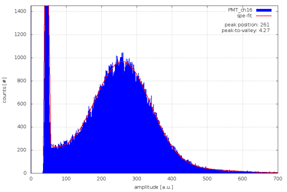
Daq mode

- FADC trigger set on Ge detectors
- if Ge triggers all other channels (Ge detectors and light detectors) are readout simultanously

extract trigger position & energy of traces

First commissioning data with calibration source

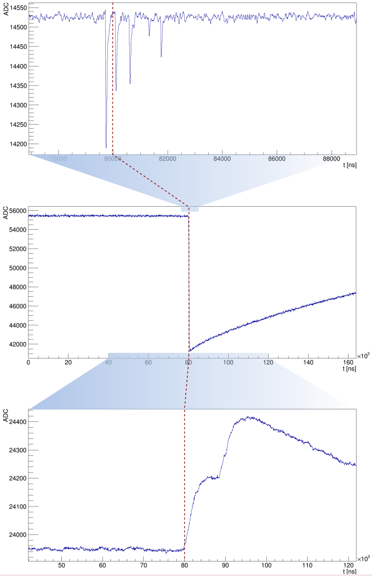
PMT gain calibration & monitoring



- gain adjusted to $1.9 \cdot 10^6$
- peak-to-valley: ≈ 4
- monitor rates & gain

PMT rates

- determine rates from first $2\,\mu\mathrm{s}$ of FADC traces
- w/o source: $200 - 300\,\mathrm{Hz}$



PMT (x16)

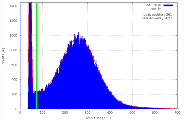
Ge diode (x8)

SiPM (x15)

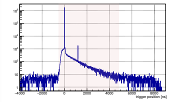
extract trigger position & energy of traces

First commissioning data with calibration source

event vetoed ?



threshold for spe set in the valley



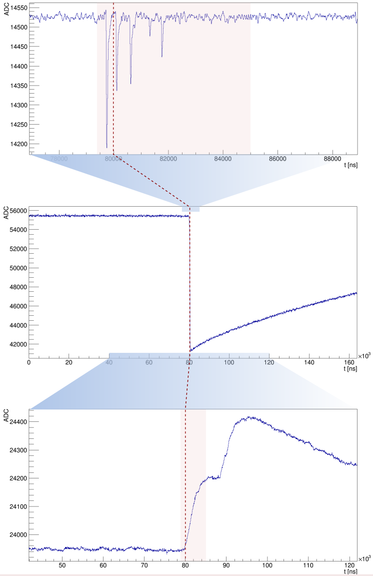
veto window choosen according to trigger distribution in the trace

⇒ **set veto flag if one photo electron is detected inside veto window in any channel**

outlook

maximize SF · acc (threshold, window)

➢ acceptance accessible via random coincidences with pulser events



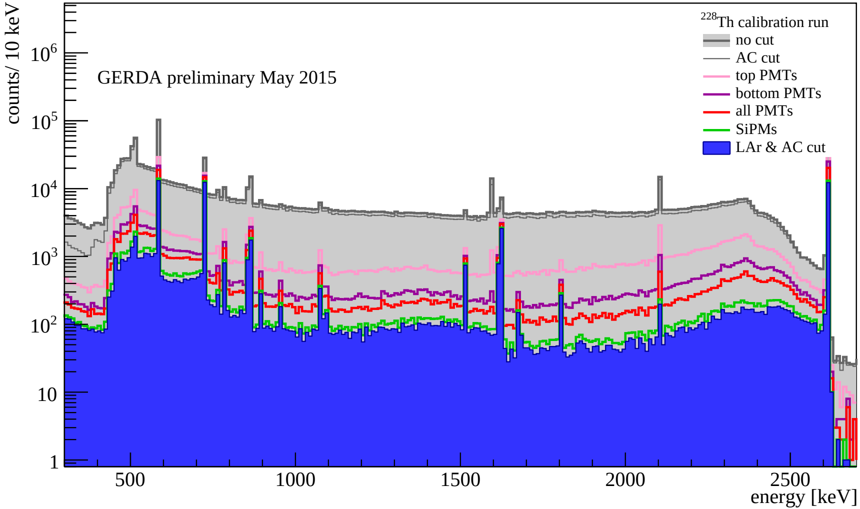
PMT (x16)

Ge diode (x8)

SiPM (x15)

extract trigger position & energy of traces

LAr veto performance of different light readouts - ^{228}Th calibration



	top PMTs	bottom PMTs	all PMTs	Fiber	LAr veto
SF in ROI	4.7 ± 0.1	12.9 ± 0.1	22.5 ± 0.3	48.0 ± 0.9	60.0 ± 1.2

$Q_{\beta\beta} \pm 200$ keV excl. SEP of ^{208}Tl., AC cut for MC comparison

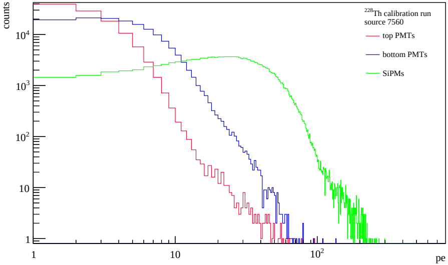
Comparison to MC simulation - ^{228}Th calibration

	SF(data)	SF (MC)
top PMTs	4.7 ± 0.1	43.3 ± 0.5
bot PMTs	12.9 ± 0.1	46.1 ± 0.6
all PMTs	22.5 ± 0.3	68.0 ± 1.0
SiPMs	48.0 ± 0.9	97.0 ± 1.7
all	60.0 ± 1.2	97.4 ± 1.7

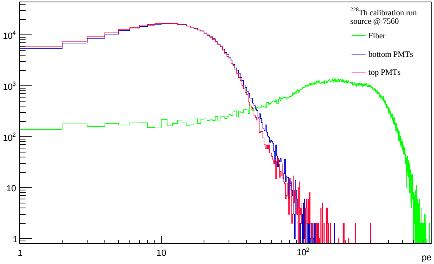
$\Rightarrow$ SF and pe yield significantly lower than predicted by MC simulations

- possible reasons:
  - fiber implementation in MC
  - optical properties

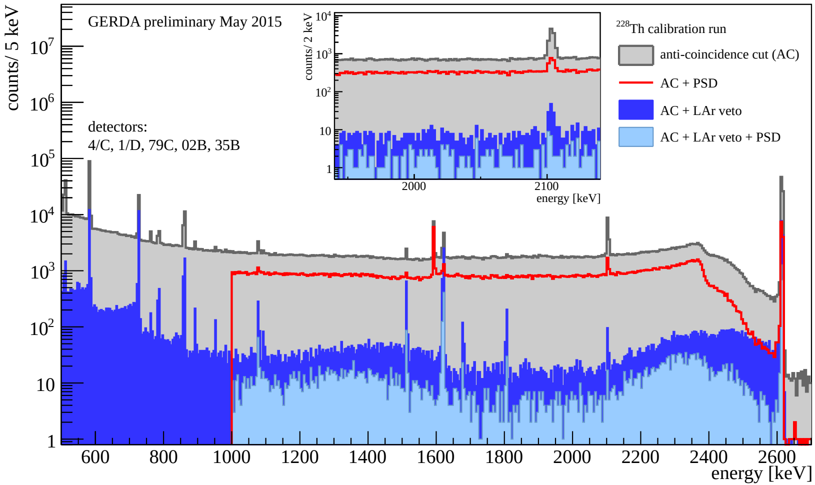
data



MC



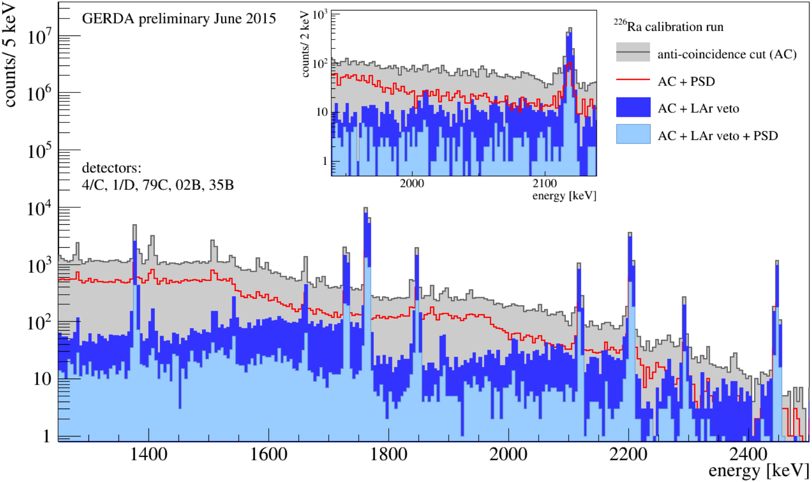
Combined LAr veto & PSD performance - ^{228}Th calibration



	AC	LAr veto	PSD	LAr+PSD
SF in ROI	1.256 ± 0.003	97.9 ± 3.7	2.19 ± 0.01	344.6 ± 24.5

86.8% acceptance for pulser, ROI: $Q_{\beta\beta} \pm 100\,\mathrm{keV}$, excl. SEP of ^{208}Tl.

Combined LAr veto & PSD performance - ^{226}Ra calibration



	AC	LAr veto	PSD	LAr+PSD
SF	1.26 ± 0.01	5.7 ± 0.2	2.98 ± 0.06	29.4 ± 2.5

89.9% acceptance for pulser, ROI: $2023 - 2047\,\mathrm{keV}$ && $2059 - 2074\,\mathrm{keV}$

Summary & outlook

- Phase I of the GERDA experiment successfully completed
  $T^{0\nu}_{1/2}(90\%\mathrm{C.L.}) > 2.1 \cdot 10^{25} yr$
- MC campaign performed to find optimal veto design
- LAr light instrumentation fully operational
- LAr veto performance with calibration sources
  - ^{228}Th: SF $= 97.9 \pm 3.7$
  - ^{226}Ra: SF $= 5.7 \pm 0.2$
- data and MC not yet in agreement

⇒ Phase II physics data taking with the light instrumentation will start soon

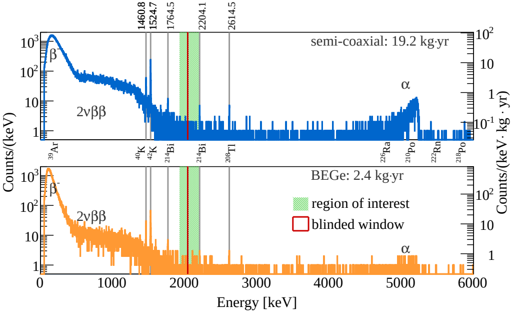
Bonus slides

data taking of PhaseI

- Nov 2011 - May 2013: 8 coaxial detectors
- 2 detectors not considered due to high leakage current
- total mass: 14.6 kg

- July 2012 - May 2013: 5 BEGes
- 1 detector not considered due to unstable behavior
- total mass: 3.0 kg

- β-spectrum of ^{39}Ar (with Q=565 keV
- $2\nu\beta\beta$-spectrum of ^{76}Ge
- γ-lines of ^{40}K, ^{42}K, ^{60}Co, ^{214}Bi, ^{212}Bi and ^{208}Tl
- α-spectrum of ^{238}U chain (in semi-coaxial detectors)

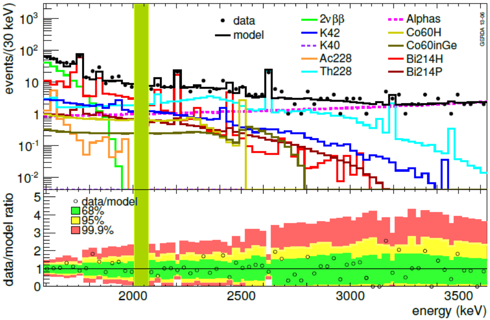


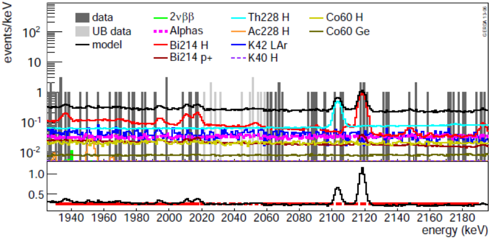
data set	Exposure [kg · y]	FWHM @ $Q_{\beta\beta}$ [keV]
golden	17.9	4.8 ± 0.2
silver	1.3	4.8 ± 0.2
BEGe	2.4	3.2 ± 0.2

region of interest (ROI) = interval @ $[1930 - 2190]\,keV$

blinded window @ $Q_{\beta\beta} \pm 20$ keV to not bias analysis

Background modeling





Contribution at $Q_{\beta\beta}$

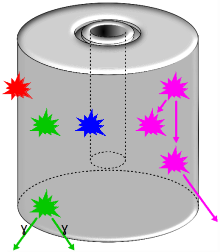
- γ-rays (close sources): ^{214}Bi, ^{208}Tl
- α and β-decays (surface decays): ^{226}Ra daugther, ^{210}Po, ^{42}K

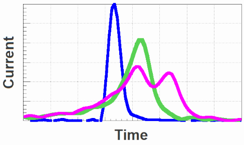
Result

- no γ-line expected in blinded window
- background flat between $[1930 - 2190]\,keV$ (excluding peaks at 2104 and 2119 keV)
- "golden":
  BI$= 1.75^{+0.26}_{-0.24} \cdot 10^{-2} \frac{cts}{kg \cdot keV \cdot yr}$
  "BEGe":
  BI$= 3.6^{+1.3}_{-1.0} \cdot 10^{-2} \frac{cts}{kg \cdot keV \cdot yr}$

Pulse shape discrimination in GERDA Phase I

Which pulse shapes can we distinguish?





- Single site event (SSE): $0\nu\beta\beta$-events, $2\nu\beta\beta$-events, DEP events
- Multi site event (MSE): have multiple compton scattering in the detector e.g. SEP events, FEP events
- Slow rising pulses: β-particles entering the detector via the n^+ surface
- Fast rising pulses: α-particles on the p^+ contact

Coaxial: 3 independent pulse shape selections performed

- Neural network analysis (ANN)
- Likelihood classification
- PSD selection based on pulse assymetry

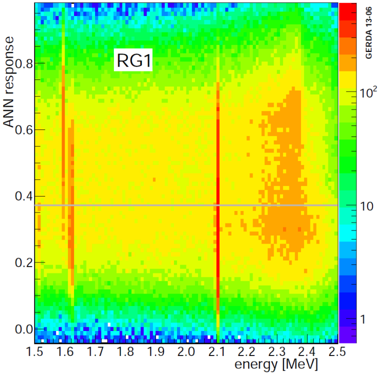
BEGe: Based on A/E method

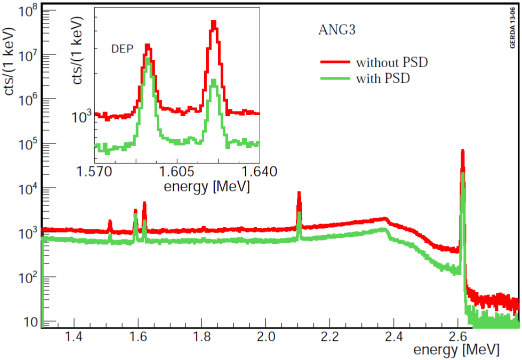
- $\epsilon_{PSD} = 0.92 \pm 0.02$
- $\sim 85\%$ of background events at $Q_{\beta\beta}$ are rejected

Training the neural network with calibration data

- Input parameters: timing information on rising part of the charge pulse
- Output: Qualifier between 0 (background event) and 1 (signal-like)

- DEP events in the interval $1592\,\mathrm{keV} \pm 1 FWHM$ serve as proxy for SSE
- Full energy line of ^{212}Bi in the equivalent interval around $1620\,\mathrm{keV}$ are dominantly MSE, taken as background events





Training the neural network with calibration data

- Input parameters: timing information on rising part of the charge pulse
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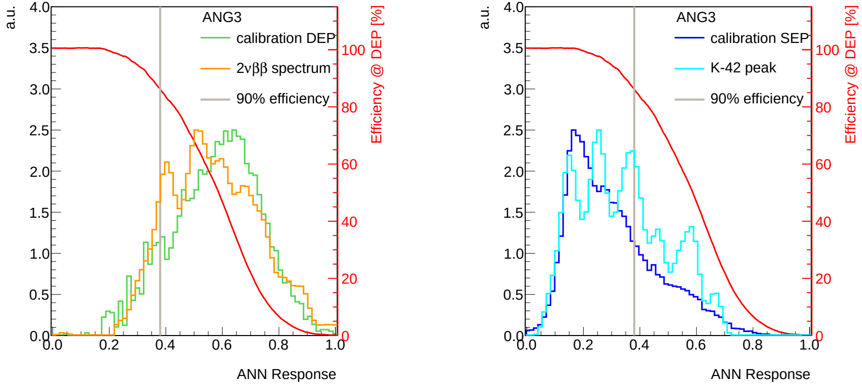
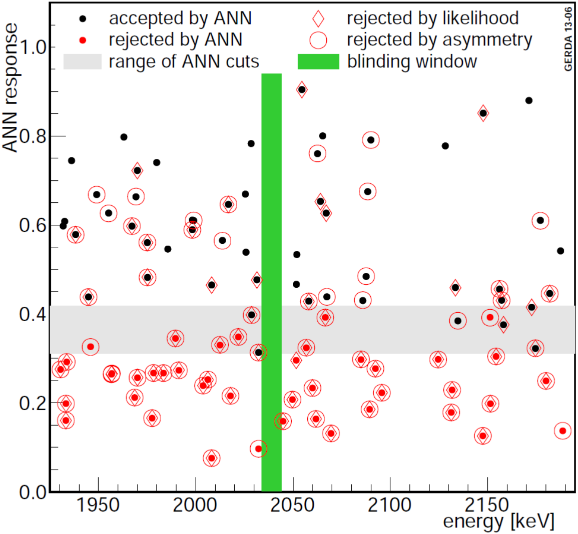


Application to Phase I data



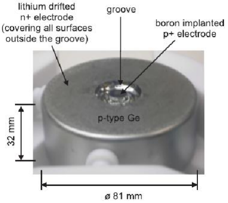
⇒ About 45% of events are rejected by ANN

Efficiency: $\epsilon_{0\nu\beta\beta} = 0.90^{+0.05}_{-0.09}$

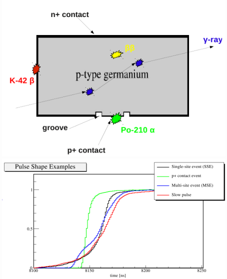
- all events removed by ANN are removed by at least one other method
- events discarded by ANN are in 90% of the cases discarded by all 3 methods
- in a larger energy window about 3% are only rejected by ANN

Broad Energy Germanium (BEGe) detectors as the GERDA Phase II detectors will improve the sensitivity by

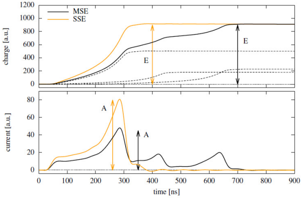
- improved energy resolution $\Delta(E)$
- enhanced pulse shape discrimination against background events

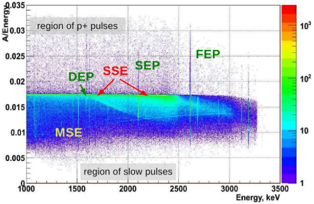


Which pulse shapes can we distinguish?



- $0\nu\beta\beta$-events are single site events (SSE)
- SSE by γ-rays are signal like and cannot be rejected
- γ-rays can interact via multiple compton scattering (MSE)
- β-particles enter the detector via the n^+ surface and produce slow pulses
- α-particles enter the detector through the region of the p^+ contact producing a comparatively high signal

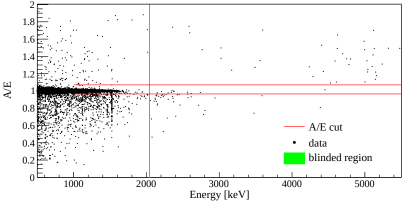


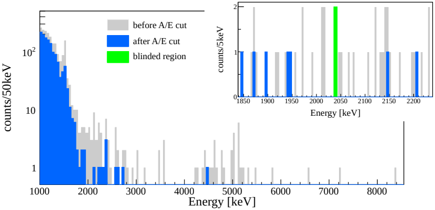


Pulse Shape Analysis (PSA)

- Use the ratio of the amplitude of the current signal A and the energy E: A/E
- A/E cut determined in PSA of a ^{228}Th spectrum:
  - SSE are located on a horizontal lines
  - MSE are found below the SSE lines
  - single escape peak (SEP) of the 2614.5 keV line contains a high fraction of MSE
  - prominent double escape peak (DEP at 1592.5 keV) of the ^{208}Tl-line which contains a high fraction of SSE

Application of the PSD to data

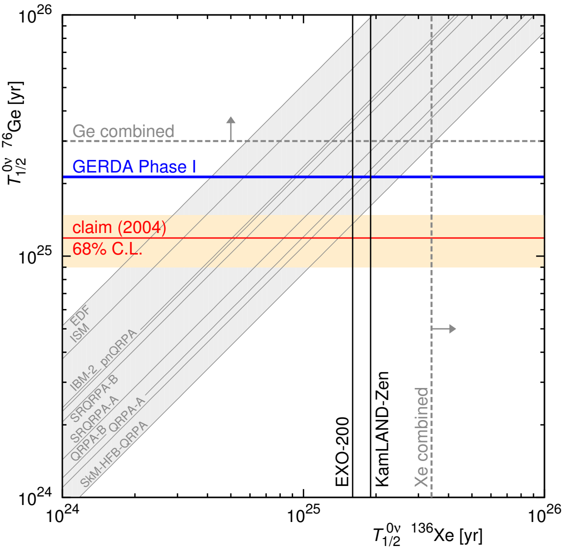




- data of all detectors added (after all corrections and normalization)
- cut levels: $A/E < 0.965$ & $A/E > 1.07$
- $Q_{\beta\beta} \pm 200\,\mathrm{keV}$: 7 out of 40 events survive PSD cut, 30 are below, 3 above

$\Rightarrow$ Background Index: $(0.042 \pm 0.007) cts/(keV \cdot kg \cdot yr)$ after PSD $0.007^{+0.004}_{-0.002}\,\mathrm{cts/(keV \cdot kg \cdot yr)}$

Considering the limits of $0\nu\beta\beta$ decay search in Xenon...



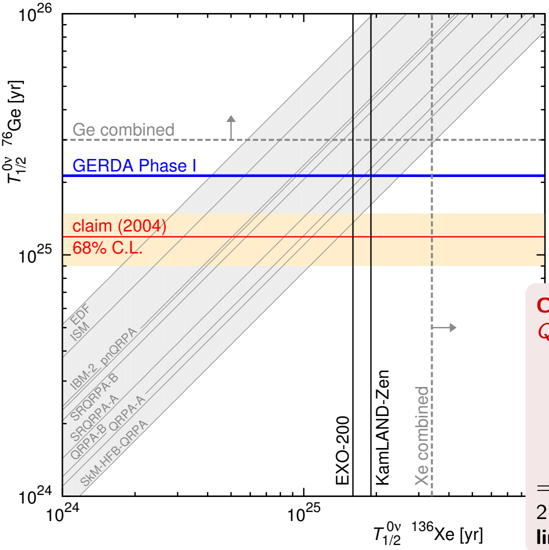
- assuming light Majorana neutrino exchange is dominanting mechanism
- exclusion of KK claim is for Xenon experiments model dependent

$$\mathbf{T^{0\nu}_{1/2}}(^{136}Xe) \propto T^{0\nu}_{1/2}(^{76}Ge) \cdot \left| \frac{\mathcal{M}_{0\nu}(^{76}Ge)}{\mathcal{M}_{0\nu}(^{136}Xe)} \right|^2$$

⇒ Bayes factor(EXO): 0.23
Bayes factor(KamLAND-Zen): 0.40

⇒ **Including the GERDA result**
Bayes factor: 0.0022

Considering the limits of $0\nu\beta\beta$ decay search in Xenon...



- assuming light Majorana neutrino exchange is dominanting mechanism
- exclusion of KK claim is for Xenon experiments model dependent

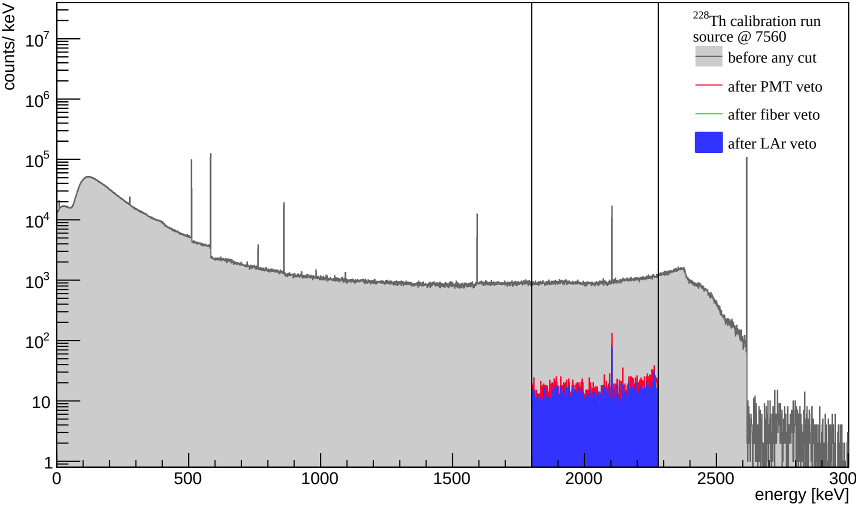
$\mathbf{T^{0\nu}_{1/2}}(^{136}Xe) \propto$

Comparison of the background level in $Q_{\beta\beta} \pm 2\sigma$ [cts/mol · yr]

- GERDA: 0.01
- EXO: 0.07
- KamLAND-Zen: 0.67

$\Rightarrow$ **GERDA** establishes after only $21.6\,\mathrm{kg}\cdot\mathrm{yr}$ the **most stringent half-life limit for** ^{76}Ge

MC sum spectrum



Comparison MC & data

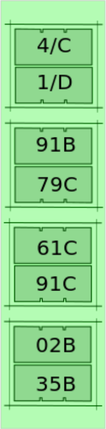
suppression factor of total string & individual detectors

$Q_{\beta\beta} \pm 200 keV$

		top PMTs	bot PMTs	PMTs	SiPMs	LAr
4/C	data	6.0 ± 0.1	12.8 ± 0.2	29.2 ± 0.7	82.9 ± 3.6	113.3 ± 5.7
	MC	63.3 ± 1.9	51.6 ± 1.4	93.4 ± 3.4	148.4 ± 6.6	148.9 ± 6.7
1/D	data	5.1 ± 0.1	13.2 ± 0.2	25.2 ± 0.6	65.8 ± 2.8	83.8 ± 3.7
	MC	58.1 ± 1.9	58.3 ± 1.9	99.9 ± 4.1	154.9 ± 7.8	155.5 ± 7.8
79C	data	4.1 ± 0.1	13.4 ± 0.2	19.9 ± 0.3	40.6 ± 1.0	50.5 ± 1.4
	MC	37.8 ± 0.9	44.1 ± 1.2	59.3 ± 1.8	80.5 ± 2.8	81.1 ± 2.8
35B	data	4.0 ± 0.1	17.2 ± 1.0	23.6 ± 1.6	40.1 ± 3.5	52.4 ± 5.2
	MC	21.9 ± 1.4	29.8 ± 2.2	35.6 ± 2.8	45.9 ± 4.0	45.9 ± 4.0
02B	data	4.0 ± 0.1	21.8 ± 1.7	29.5 ± 2.7	43.1 ± 4.8	63.9 ± 8.6
	MC	21.6 ± 1.6	30.6 ± 2.7	34.0 ± 3.1	43.8 ± 4.5	43.8 ± 4.5
all	data	4.8 ± 0.1	13.4 ± 0.1	23.6 ± 0.3	54.0 ± 1.0	69.1 ± 1.4
	MC	43.3 ± 0.5	46.1 ± 0.6	68.0 ± 1.0	97.0 ± 1.7	97.4 ± 1.7
acceptance		97.76%	96.55%	95.49%	88.87%	86.78%

- SF of data is not yet corrected for the pulser acceptance !!!

Ra226 calibration with MS (20150430)

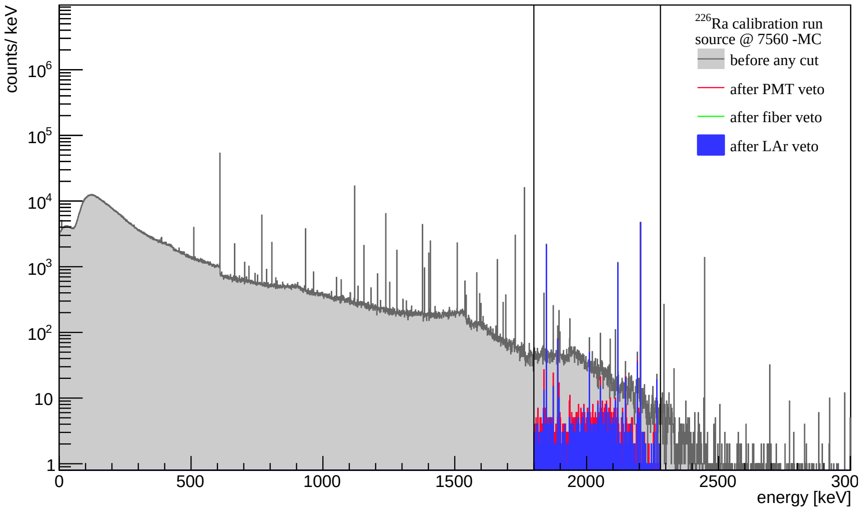


- data from IntegrationTest_20150528
- ^{226}Ra source @ position 7560 (with MS)
- identical detector configuration (Ge & LAr) as in ^{228}Th calibration

⇒ analysis for the comparison of data and MC is restricted to these detectors

- for the plots showing combined results (LAr veto performance and PSD) not fully depleted detectors are used for AC

MC



counts/ keV
10^6
10^5
10^4
10^3
10^2
10
1
0
500
1000
1500
2000
2500
300
energy [keV]
^{226}Ra calibration run
source @ 7560 -MC
before any cut
after PMT veto
after fiber veto
after LAr veto

Comparison MC & data

suppression factor of total string

$Q_{\beta\beta} \pm 35 keV$ excluding gamma lines

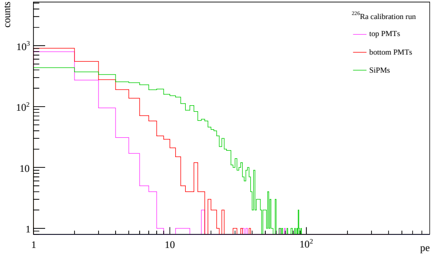
		top PMTs	bottom PMTs	PMTs	SiPMs	LAr
4/C	data	1.6 ± 0.1	1.9 ± 0.1	2.5 ± 0.1	4.7 ± 0.3	5.5 ± 0.1
	MC	4.3 ± 1.9	3.7 ± 1.5	5.2 ± 2.4	7.4 ± 3.8	7.4 ± 3.8
1/D	data	1.5 ± 0.1	2.2 ± 0.1	2.6 ± 0.1	4.2 ± 0.2	5.0 ± 0.3
	MC	5.9 ± 2.2	4.9 ± 1.7	8.3 ± 3.5	11.9 ± 5.8	11.9 ± 5.8
79C	data	1.4 ± 0.1	2.0 ± 0.1	2.3 ± 0.1	3.1 ± 0.1	3.6 ± 0.1
	MC	4.3 ± 0.8	4.9 ± 0.9	5.3 ± 1.3	11.5 ± 3.0	11.5 ± 3.0
35B	data	1.4 ± 0.1	2.6 ± 0.2	2.9 ± 0.2	3.3 ± 0.3	4.3 ± 0.4
	MC	3.7 ± 0.7	5.2 ± 1.1	5.8 ± 1.3	7.2 ± 1.7	7.2 ± 1.7
02B	data	1.6 ± 0.1	4.3 ± 0.5	4.9 ± 0.6	5.4 ± 0.7	8.1 ± 1.4
	MC	5.4 ± 1.1	7.6 ± 1.8	9.0 ± 2.3	11.5 ± 3.3	11.5 ± 3.3
all	data	1.5 ± 0.1	2.1 ± 0.1	2.5 ± 0.1	3.7 ± 0.1	4.4 ± 0.3
	MC	4.1 ± 0.3	5.4 ± 0.4	5.4 ± 0.6	9.3 ± 0.9	9.3 ± 0.9
acc		97.81%	97.26%	95.82%	92.61%	89.90%

- SF of data is not yet corrected for the pulser acceptance !!!

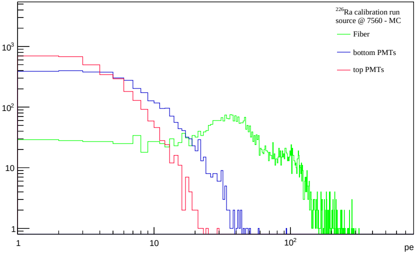
Comparison MC & data

pe yield

data



MC



	max (data)	max (MC)
SiPM	$\approx 1-3$	$\approx 40-100$
top PMTs	$\approx 1-2$	$\approx 2-3$
bot PMTs	$\approx 1-2$	$\approx 3-5$